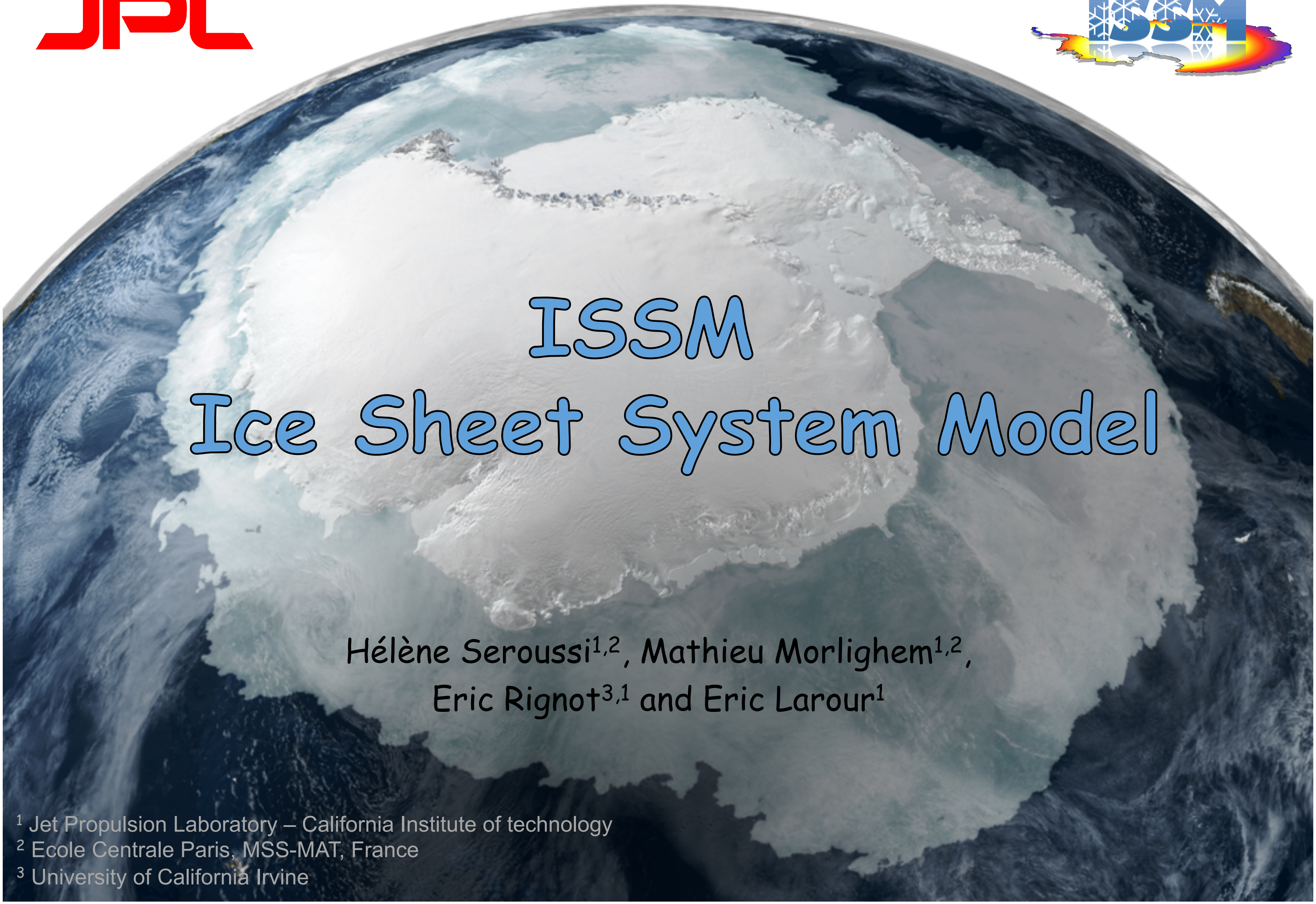

ISSM
Ice Sheet System Model

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Outline

1. Introduction
2. Ice sheet modeling
   - Velocity
   - Temperature
   - Mass conservation
3. ISSM capabilities
   - Mesh generation
   - Data assimilation
   - Velocities of Antarctica and Greenland
   - Temperatures of Antarctica and Greenland
   - Sensitivity analysis
4. Perspectives
   - ISSM - ECCO2 coupling

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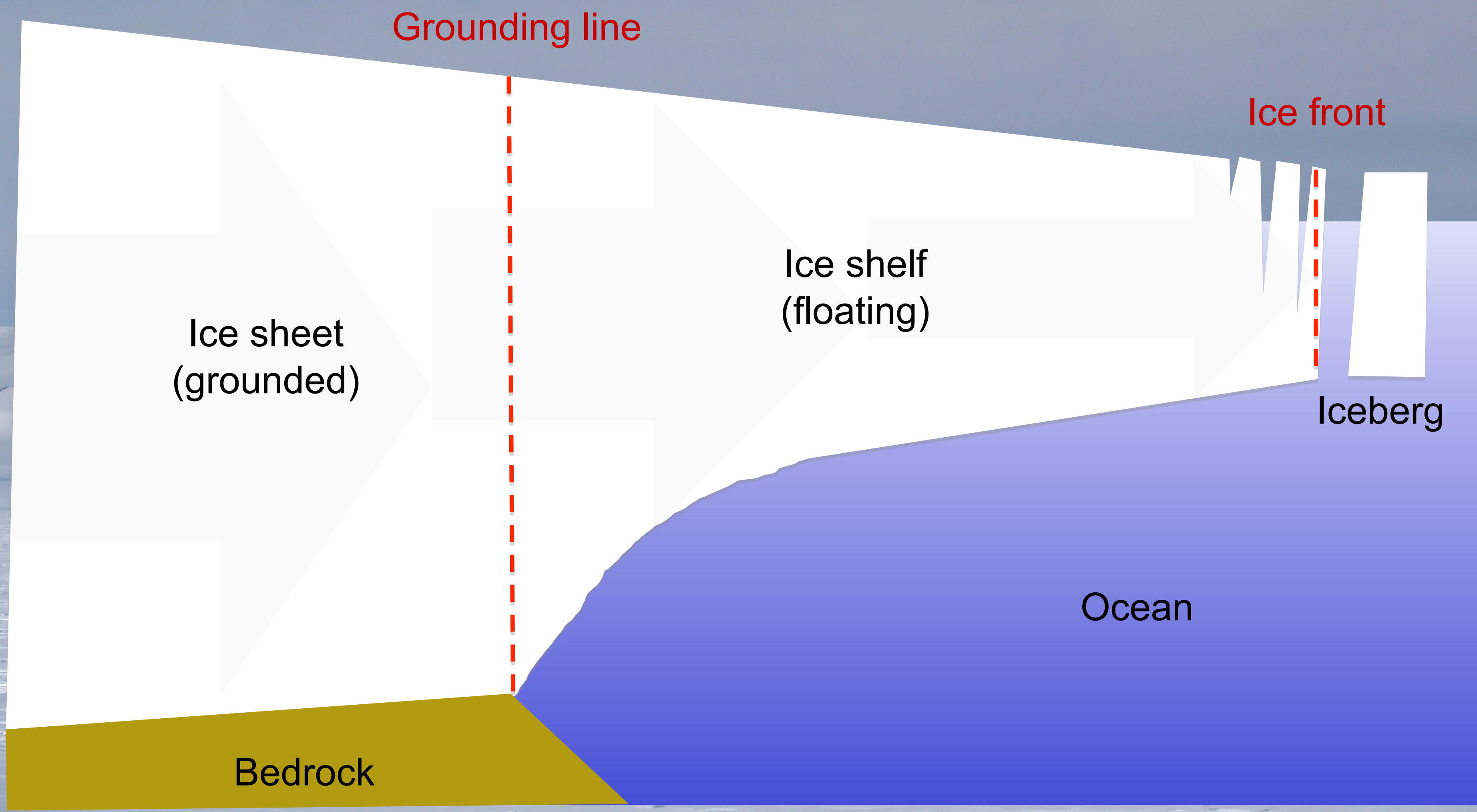
1. Introduction



1. Introduction

- ISSM: Ice Sheet System Model
- JPL/UCI collaboration to develop large-scale, high-resolution ice-sheet modeling with remote sensing data assimilation
- Hosted in Matlab (ease of use), written in C++ (efficiency), parallelized using Petsc libraries and MPI communications

- Large-scale capability (Antarctica)
- Multi-resolution (~500m ice stream to 100km inland)
- Multi-model (2d, 3d, 2d/3d coupled, full Stokes)

- Team members:
  – Eric Rignot (team manager)
  – Eric Larour (development manager)
  – Hélène Seroussi
  – Mathieu Morlighem

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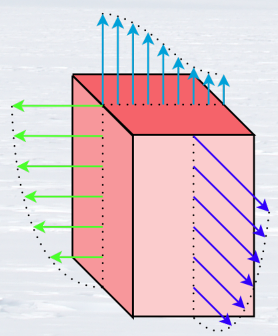
2. Ice sheet modeling

Ice flow model: Stokes

$$
\left\{
\begin{array}{l}
\dfrac{\partial}{\partial x}\left(2\mu\dfrac{\partial \boldsymbol{v}_x}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial y}+\mu\dfrac{\partial \boldsymbol{v}_y}{\partial x}\right)+\dfrac{\partial}{\partial z}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial z}+\mu\dfrac{\partial \boldsymbol{v}_z}{\partial x}\right)-\dfrac{\partial P}{\partial x}=0\\[2ex]
\dfrac{\partial}{\partial x}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial y}+\mu\dfrac{\partial \boldsymbol{v}_y}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(2\mu\dfrac{\partial \boldsymbol{v}_y}{\partial y}\right)+\dfrac{\partial}{\partial z}\left(\mu\dfrac{\partial \boldsymbol{v}_y}{\partial z}+\mu\dfrac{\partial \boldsymbol{v}_z}{\partial y}\right)-\dfrac{\partial P}{\partial y}=0\\[2ex]
\dfrac{\partial}{\partial x}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial z}+\mu\dfrac{\partial \boldsymbol{v}_z}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\mu\dfrac{\partial \boldsymbol{v}_y}{\partial z}+\mu\dfrac{\partial \boldsymbol{v}_z}{\partial y}\right)+\dfrac{\partial}{\partial z}\left(2\mu\dfrac{\partial \boldsymbol{v}_z}{\partial z}\right)-\dfrac{\partial P}{\partial z}-\rho g=0
\end{array}
\right.
$$

$$
\frac{\partial \boldsymbol{v}_x}{\partial x}+\frac{\partial \boldsymbol{v}_y}{\partial y}+\frac{\partial \boldsymbol{v}_z}{\partial z}=0
$$

Stokes



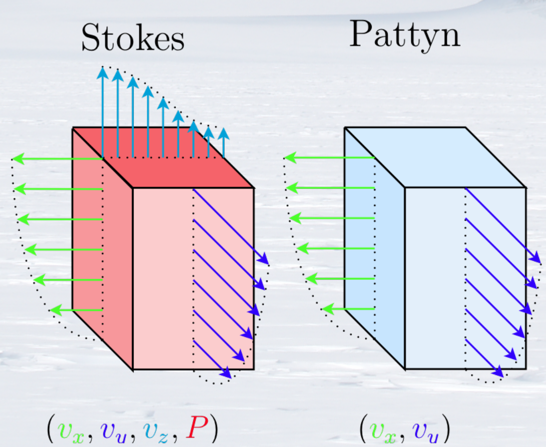
(v_x, v_y, v_z, P)

2. Ice sheet modeling

Ice flow model: Pattyn

$$
\begin{cases}
\dfrac{\partial}{\partial x}\left(2\mu\dfrac{\partial \boldsymbol{v}_x}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial y}+\mu\dfrac{\partial \boldsymbol{v}_y}{\partial x}\right)+\dfrac{\partial}{\partial z}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial z}+\cancel{\mu\dfrac{\partial \boldsymbol{v}_z}{\partial x}}\right)-\dfrac{\partial P}{\partial x}=0 \\[2ex]
\dfrac{\partial}{\partial x}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial y}+\mu\dfrac{\partial \boldsymbol{v}_y}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(2\mu\dfrac{\partial \boldsymbol{v}_y}{\partial y}\right)+\dfrac{\partial}{\partial z}\left(\mu\dfrac{\partial \boldsymbol{v}_y}{\partial z}+\cancel{\mu\dfrac{\partial \boldsymbol{v}_z}{\partial y}}\right)-\dfrac{\partial P}{\partial y}=0 \\[2ex]
\cancel{\dfrac{\partial}{\partial x}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial z}+\mu\dfrac{\partial \boldsymbol{v}_z}{\partial x}\right)}+\cancel{\dfrac{\partial}{\partial y}\left(\mu\dfrac{\partial \boldsymbol{v}_y}{\partial z}+\mu\dfrac{\partial \boldsymbol{v}_z}{\partial y}\right)}+\dfrac{\partial}{\partial z}\left(2\mu\dfrac{\partial \boldsymbol{v}_z}{\partial z}\right)-\dfrac{\partial P}{\partial z}-\rho g=0
\end{cases}
$$

$$
\frac{\partial \boldsymbol{v}_x}{\partial x}+\frac{\partial \boldsymbol{v}_y}{\partial y}+\frac{\partial \boldsymbol{v}_z}{\partial z}=0
$$

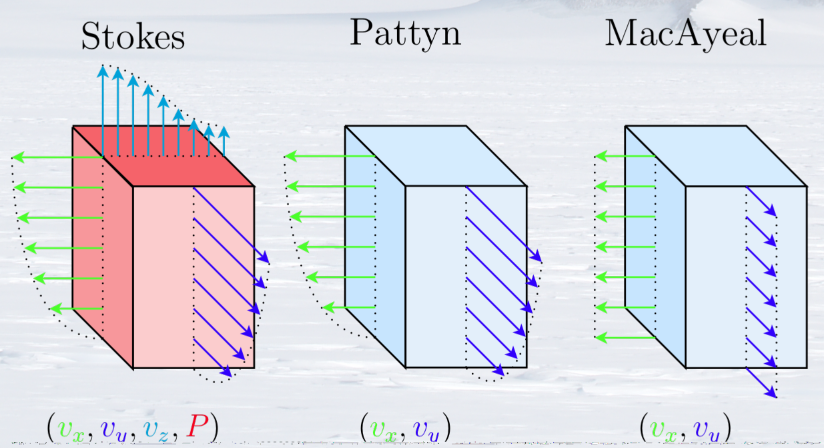


2. Ice sheet modeling

Ice flow model: MacAyeal

$$
\begin{cases}
\frac{\partial}{\partial x}\left(2\mu\frac{\partial \boldsymbol{v}_x}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial \boldsymbol{v}_x}{\partial y} + \mu\frac{\partial \boldsymbol{v}_y}{\partial x}\right) + \frac{\partial}{\partial z}\left(\mu\cancel{\frac{\partial \boldsymbol{v}_x}{\partial z}} + \mu\cancel{\frac{\partial \boldsymbol{v}_z}{\partial x}}\right) - \frac{\partial P}{\partial x} = 0 \\
\frac{\partial}{\partial x}\left(\mu\frac{\partial \boldsymbol{v}_x}{\partial y} + \mu\frac{\partial \boldsymbol{v}_y}{\partial x}\right) + \frac{\partial}{\partial y}\left(2\mu\frac{\partial \boldsymbol{v}_y}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu\cancel{\frac{\partial \boldsymbol{v}_y}{\partial z}} + \mu\cancel{\frac{\partial \boldsymbol{v}_z}{\partial y}}\right) - \frac{\partial P}{\partial y} = 0 \\
\cancel{\frac{\partial}{\partial x}\left(\mu\frac{\partial \boldsymbol{v}_x}{\partial z} + \mu\frac{\partial \boldsymbol{v}_z}{\partial x}\right)} + \cancel{\frac{\partial}{\partial y}\left(\mu\frac{\partial \boldsymbol{v}_y}{\partial z} + \mu\frac{\partial \boldsymbol{v}_z}{\partial y}\right)} + \frac{\partial}{\partial z}\left(2\mu\frac{\partial \boldsymbol{v}_z}{\partial z}\right) - \frac{\partial P}{\partial z} - \rho g = 0
\end{cases}
$$

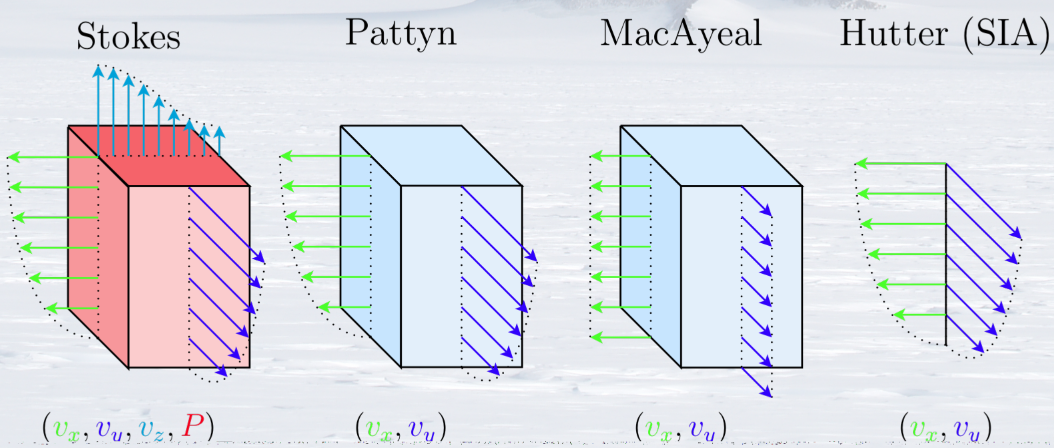
$$
\frac{\partial \boldsymbol{v}_x}{\partial x} + \frac{\partial \boldsymbol{v}_y}{\partial y} + \frac{\partial \boldsymbol{v}_z}{\partial z} = 0
$$



Ice flow model: Hutter

$$
\left\{
\begin{array}{l}
\dfrac{\partial}{\partial x}\left(2\mu\cancel{\dfrac{\partial \boldsymbol{v}_x}{\partial x}}\right)+\dfrac{\partial}{\partial y}\left(\mu\cancel{\dfrac{\partial \boldsymbol{v}_x}{\partial y}}+\mu\cancel{\dfrac{\partial \boldsymbol{v}_y}{\partial x}}\right)+\dfrac{\partial}{\partial z}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial z}+\mu\cancel{\dfrac{\partial \boldsymbol{v}_z}{\partial x}}\right)-\dfrac{\partial P}{\partial x}=0\\[2ex]
\dfrac{\partial}{\partial x}\left(\mu\cancel{\dfrac{\partial \boldsymbol{v}_x}{\partial y}}+\mu\cancel{\dfrac{\partial \boldsymbol{v}_y}{\partial x}}\right)+\dfrac{\partial}{\partial y}\left(2\mu\cancel{\dfrac{\partial \boldsymbol{v}_y}{\partial y}}\right)+\dfrac{\partial}{\partial z}\left(\mu\dfrac{\partial \boldsymbol{v}_y}{\partial z}+\mu\cancel{\dfrac{\partial \boldsymbol{v}_z}{\partial y}}\right)-\dfrac{\partial P}{\partial y}=0\\[2ex]
\cancel{\dfrac{\partial}{\partial x}\left(\mu\dfrac{\partial \boldsymbol{v}_x}{\partial z}+\mu\dfrac{\partial \boldsymbol{v}_z}{\partial x}\right)}+\cancel{\dfrac{\partial}{\partial y}\left(\mu\dfrac{\partial \boldsymbol{v}_y}{\partial z}+\mu\dfrac{\partial \boldsymbol{v}_z}{\partial y}\right)}+\dfrac{\partial}{\partial z}\left(2\mu\cancel{\dfrac{\partial \boldsymbol{v}_z}{\partial z}}\right)-\dfrac{\partial P}{\partial z}-\rho g=0
\end{array}
\right.
$$

$$
\cancel{\frac{\partial \boldsymbol{v}_x}{\partial x}}+\cancel{\frac{\partial \boldsymbol{v}_y}{\partial y}}+\cancel{\frac{\partial \boldsymbol{v}_z}{\partial z}}=0
$$



2. Ice sheet modeling

Thermal regime

- Energy balance:
  - Heat transport: conduction & advection
  - Heat sources: basal friction & deformational heating

- Boundary conditions:
  - imposed surface temperature
  - ocean / geothermal flux

$$\frac{\partial T}{\partial t} = -\left(\boldsymbol{v}_x \frac{\partial T}{\partial x} + \boldsymbol{v}_y \frac{\partial T}{\partial y} + \boldsymbol{v}_z \frac{\partial T}{\partial z}\right) + \frac{k_{th}}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\Phi}{\rho c}$$

Mass conservation: geometry evolution

- Mass conservation
  - Input
    - Mass influx
    - Surface accumulation
  - Output
    - Mass outflux
    - Bottom melting

$$\frac{\partial H}{\partial t} = -\mathrm{div}\left(H \begin{bmatrix} \bar{\boldsymbol{v}}_x \\ \bar{\boldsymbol{v}}_y \end{bmatrix} \right) + \dot{M}_s - \dot{M}_b$$

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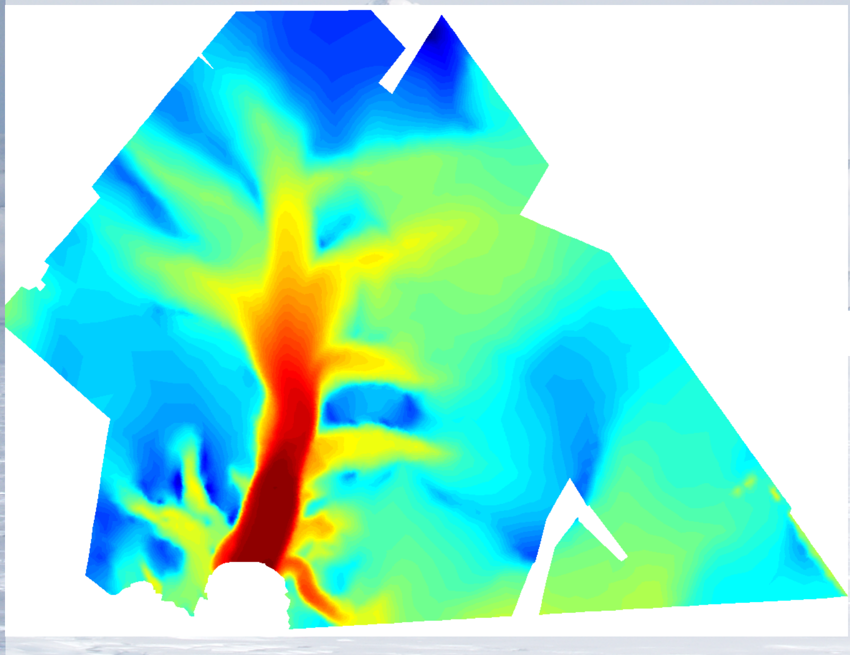
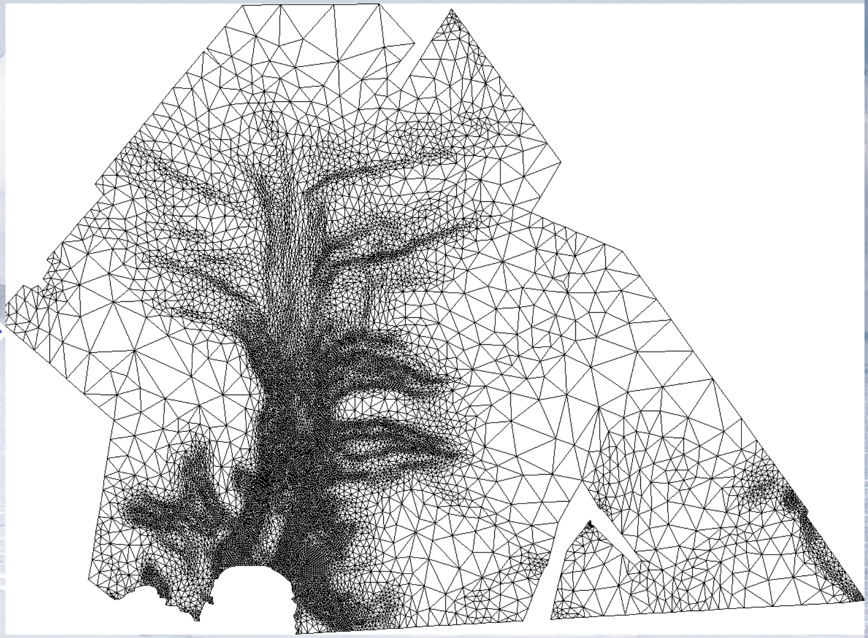
3. ISSM capabilities

Mesh generation

- Finite elements
- Triangular mesh (extruded if 3d)
- Anisotropic mesh adaptation, Yams (INRIA, Pascal Frey)



Observed velocity

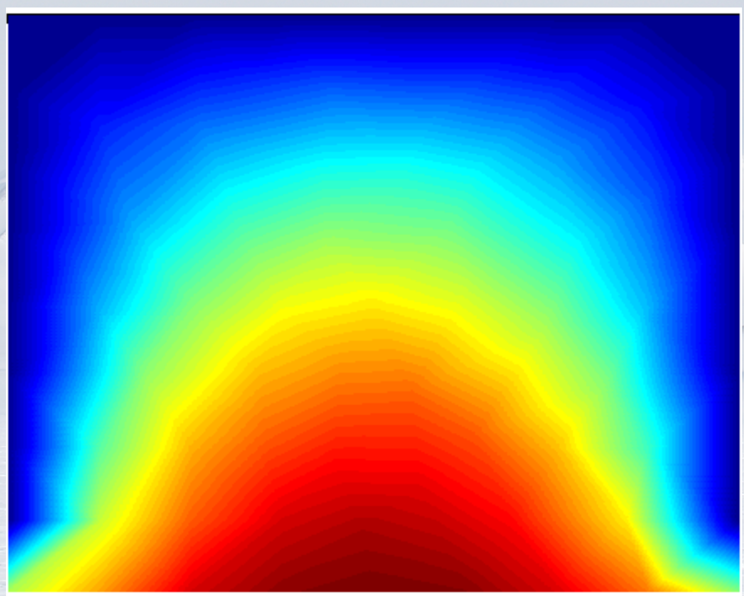


Adapted mesh

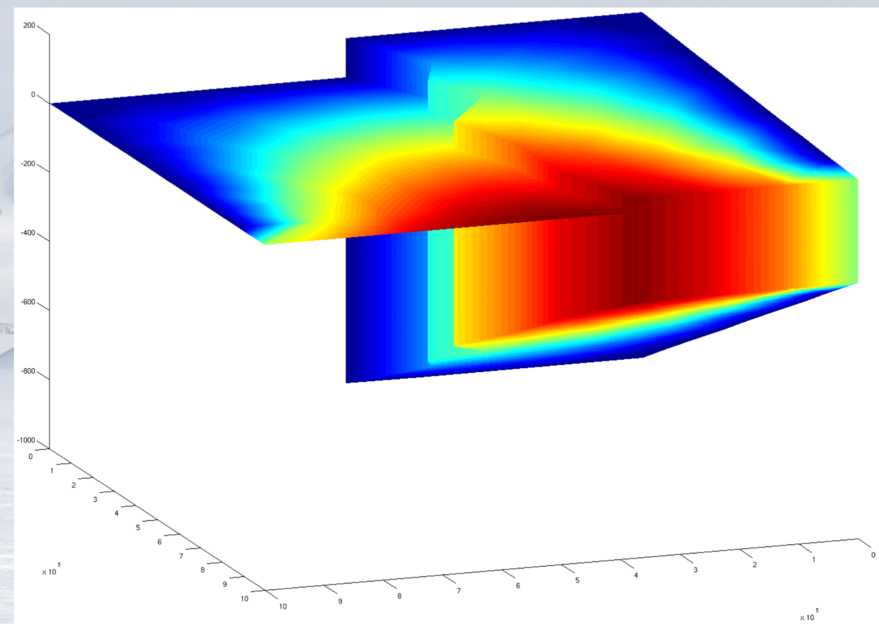
3. ISSM capabilities

Ice flow models implementation

- Multi-model: different models are connected using Rigid Body Motion connectors, or method of penalties.



Surface velocity



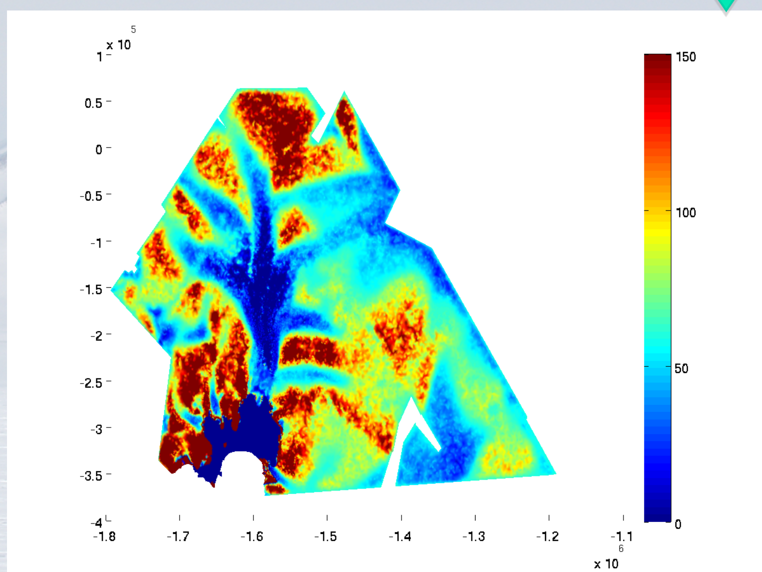
3d view

2. ISSM capabilities

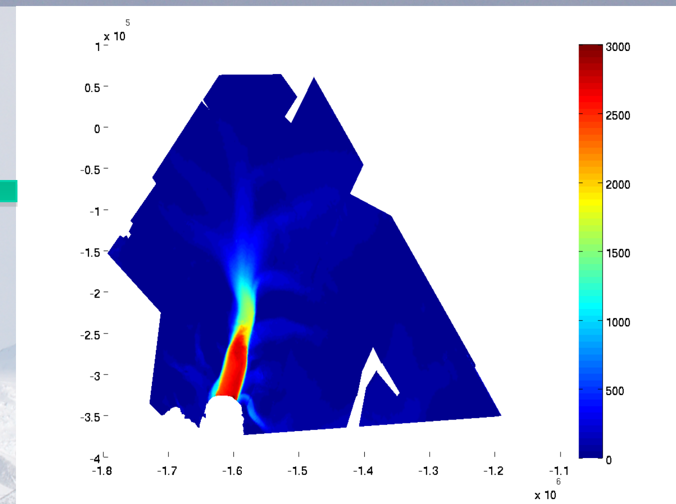
Data assimilation: control methods

Find the spatial pattern of basal drag that minimizes the misfit between the observed and the modeled velocities

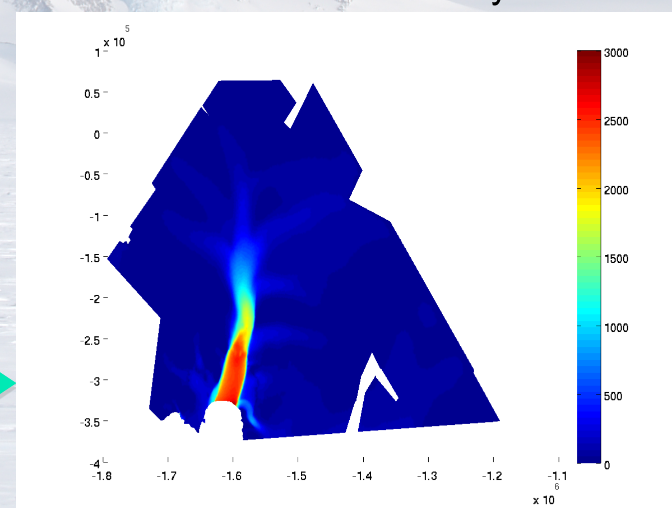
$$\overrightarrow{\tau_b} \quad = \quad -\alpha^2 N_{eff}^r ||\overrightarrow{v}||^{s-1}\overrightarrow{u_b}$$



Drag coefficient α



Observed velocity



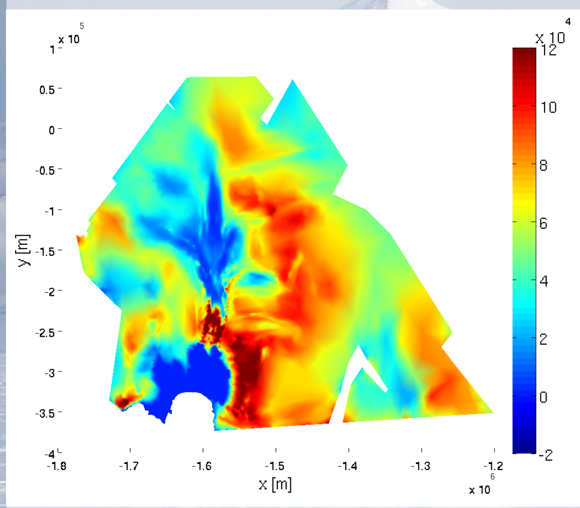
Modeled velocity

2. ISSM capabilities

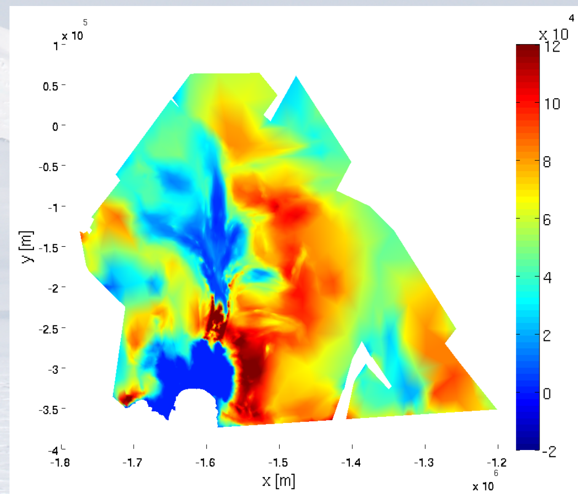
Data assimilation: Basin level

Higher-order data assimilation:

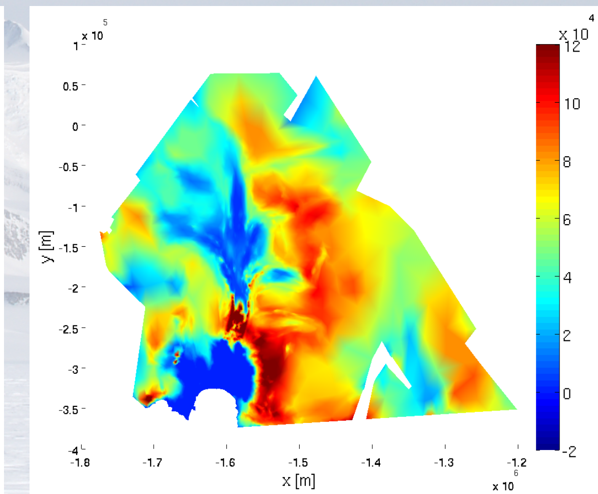
- MacAyeal, Pattyn and Stokes formulations at the basin level



2D MacAyeal
Basal drag (kPa)



3D Pattyn
Basal drag (kPa)



3D Stokes
Basal drag (kPa)

2. ISSM capabilities

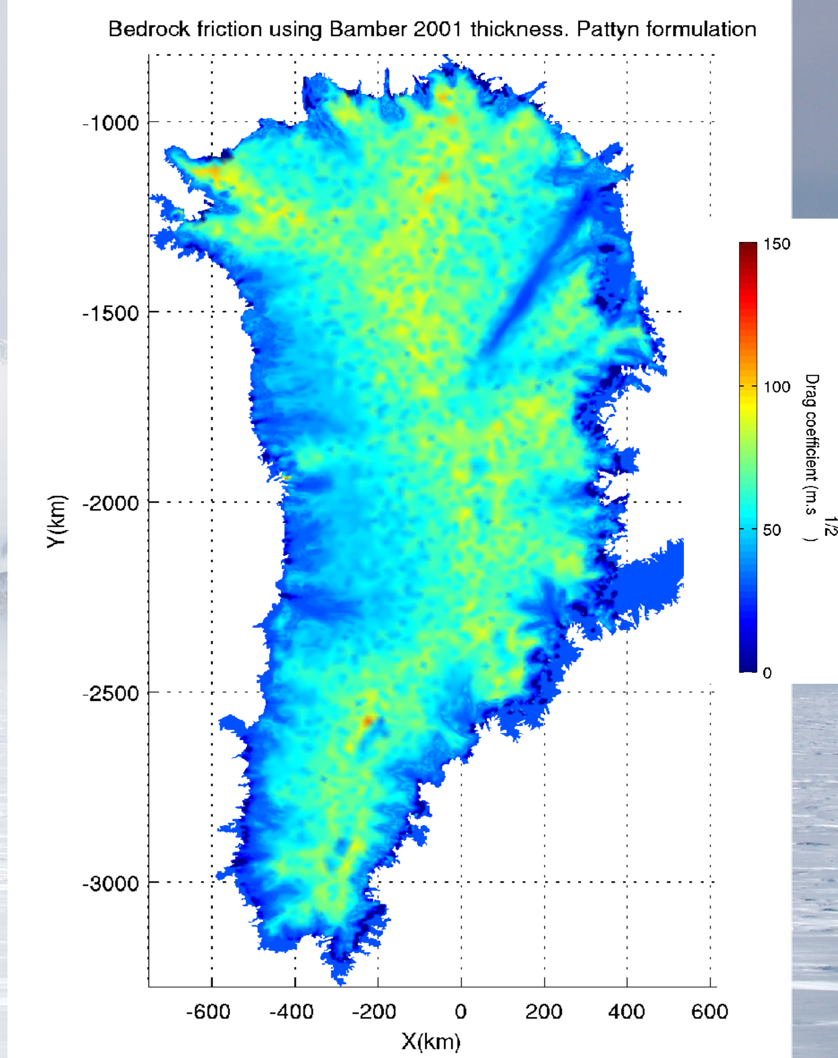
Data assimilation: Continental level

Model:

- Data assimilation for basal drag using surface velocity from InSAR (Rignot) + balanced velocities (Bamber 2001)

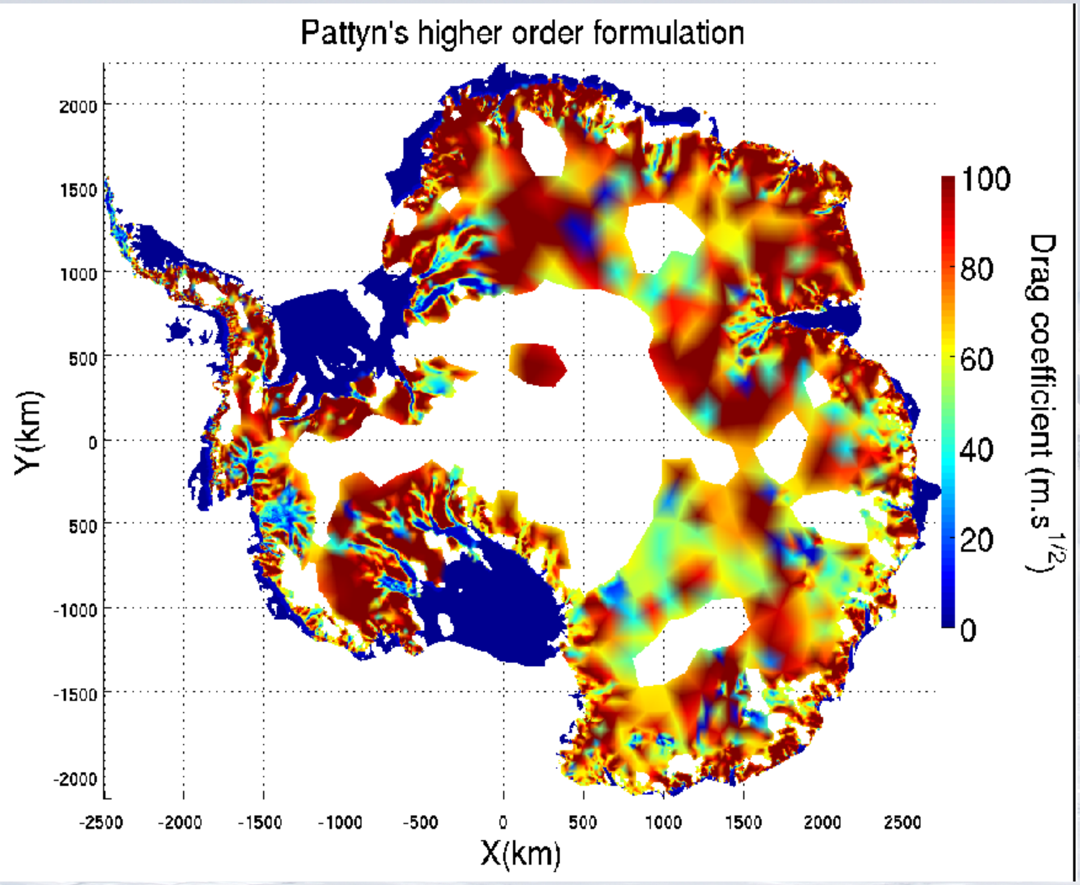
Run statistics:

- 128 CPUS cluster, 12 h computation
- 500 m resolution at basins, 10 km inland
- 10 vertical layers



2. ISSM capabilities

Data assimilation: Continental level



Model:

- Data assimilation for basal drag, using surface velocity from InSAR (Rignot)

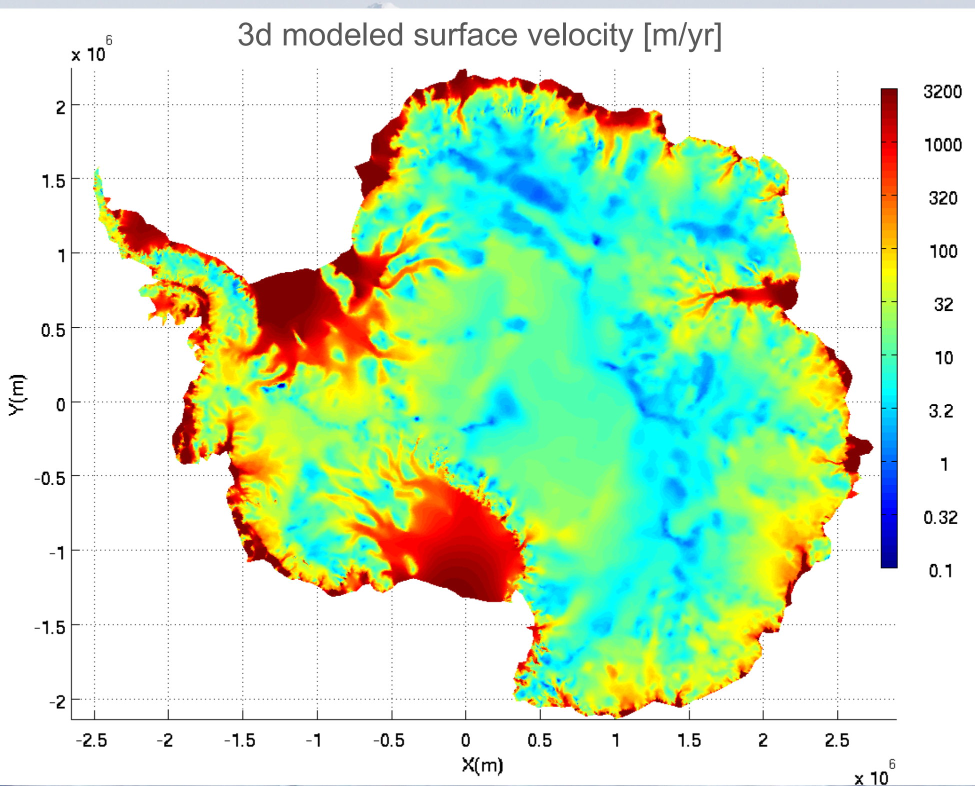
Run statistics:

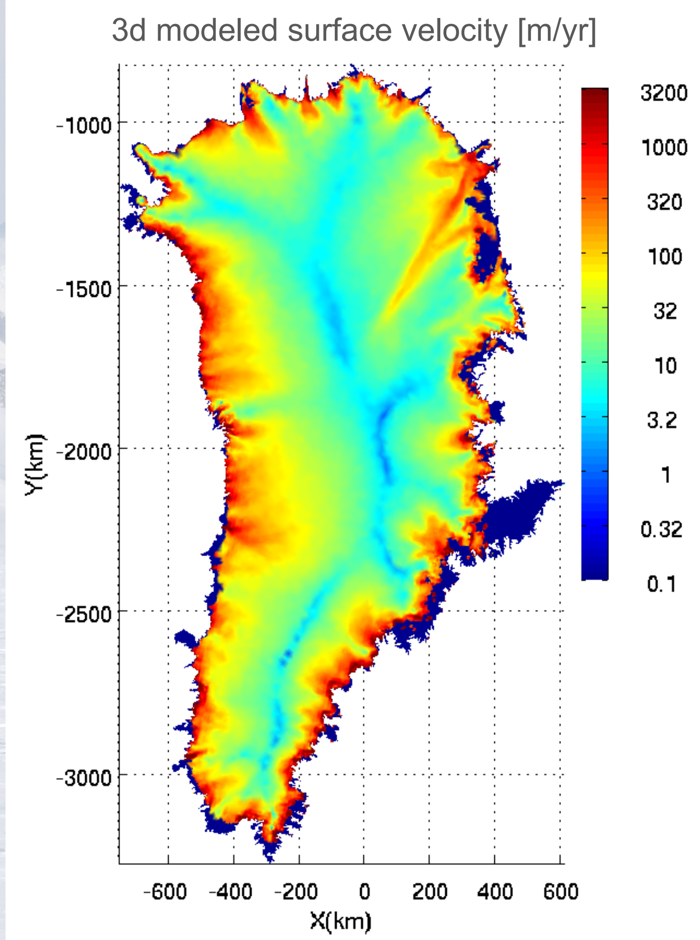
- 128 CPUS cluster
  18 hr computation
- 1.5km resolution at basins
  10 km inland
- 10 vertical layers

2. ISSM capabilities

Spatial resolution and geographic coverage

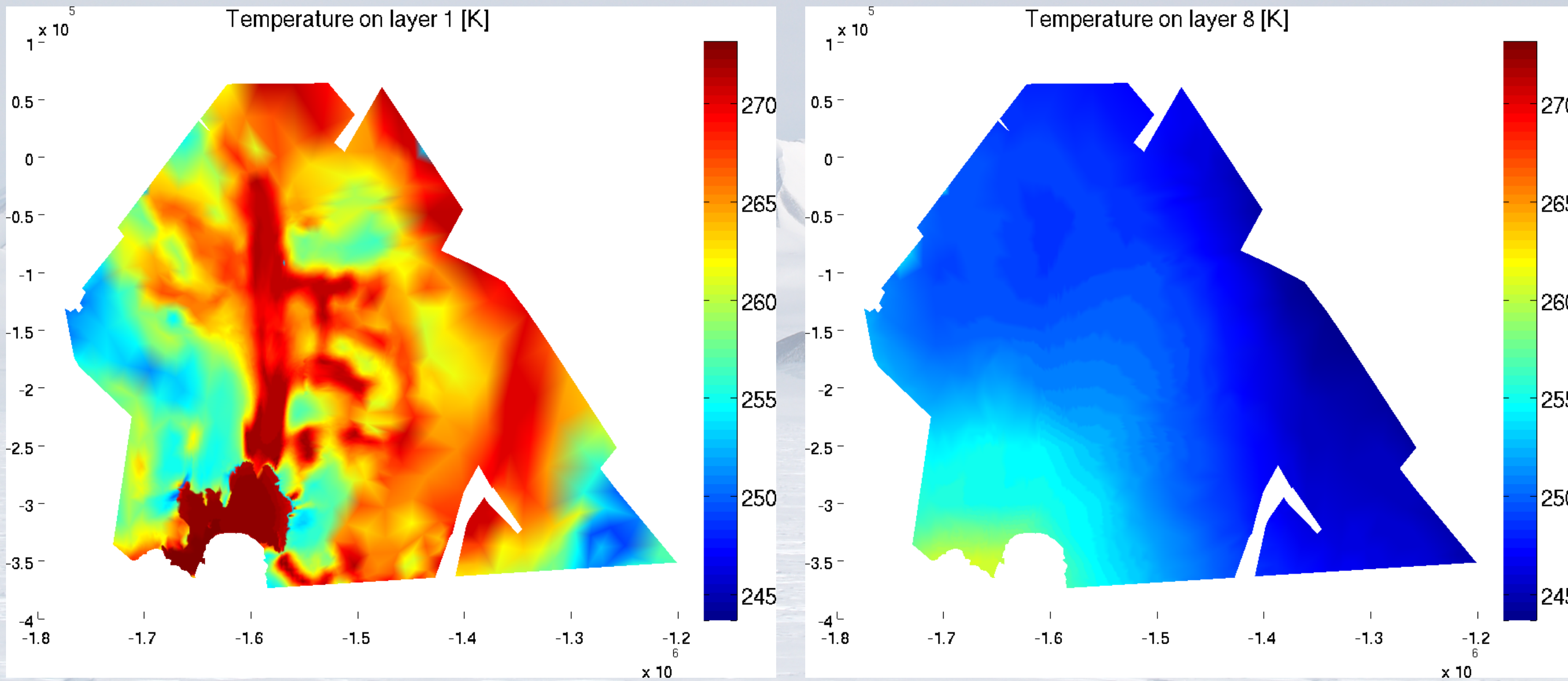
- Large scale capability:
  - 5 million dof on 256 CPU cluster (shared or distributed memory)
  - ~1 km resolution on Antarctica's ice streams
  - < 1km resolution on Greenland basins
  - 10 vertical layers





Thermal regime: Basin scale

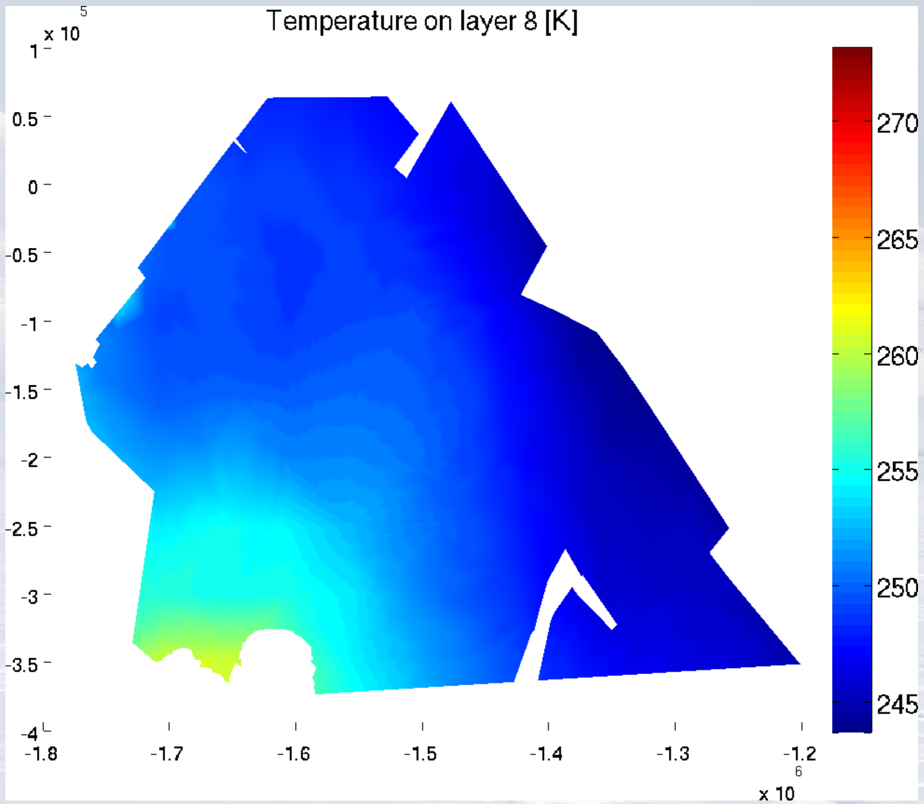
- Thermal regime: steady-state & transient
  - SUPG stabilization
  - Melting is a by-product of thermal modeling using penalties



Steady-state temperature of Pine Island Glacier, West Antarctica

Thermal regime: Basin scale

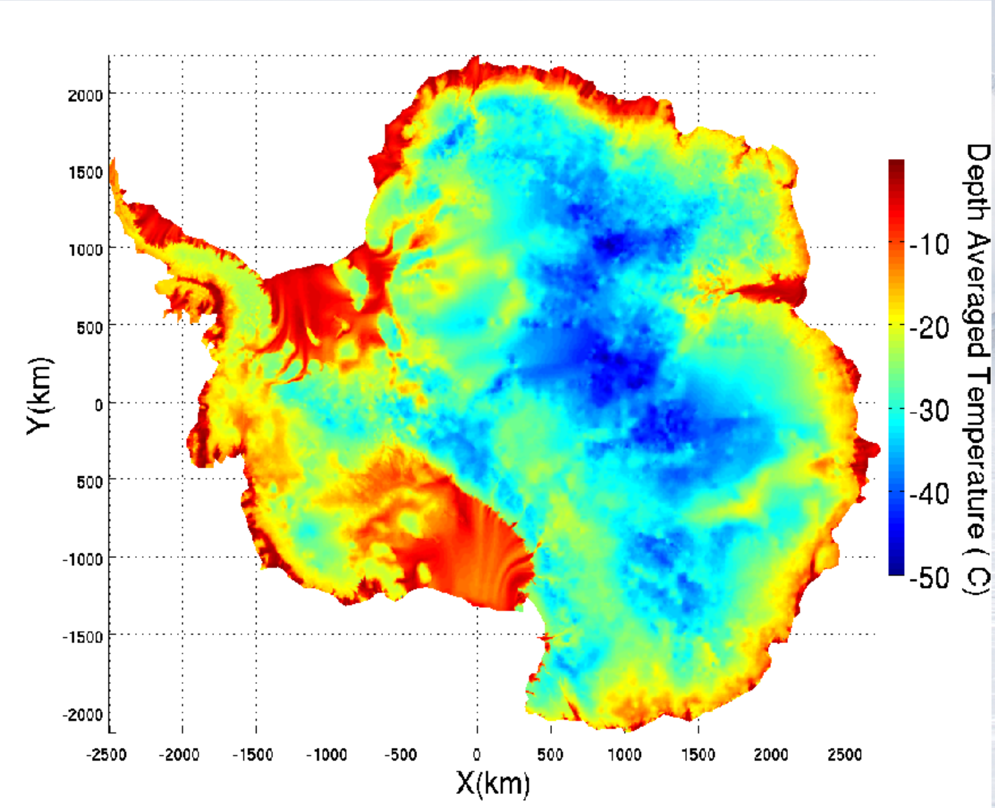
- Thermal regime: steady-state & transient
  - SUPG stabilization
  - Melting is a by-product of thermal modeling using penalties

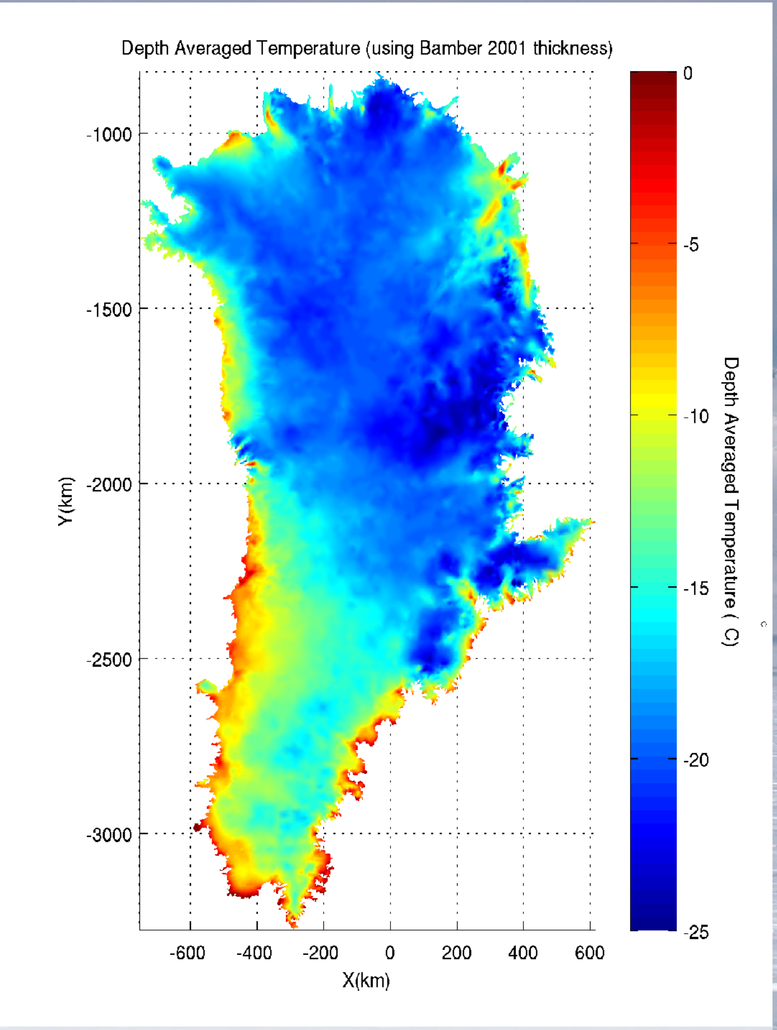


Steady-state temperature of Pine Island Glacier, West Antarctica

Thermal regime: Continental scale

Thermal regime: steady-state of Greenland & Antarctica

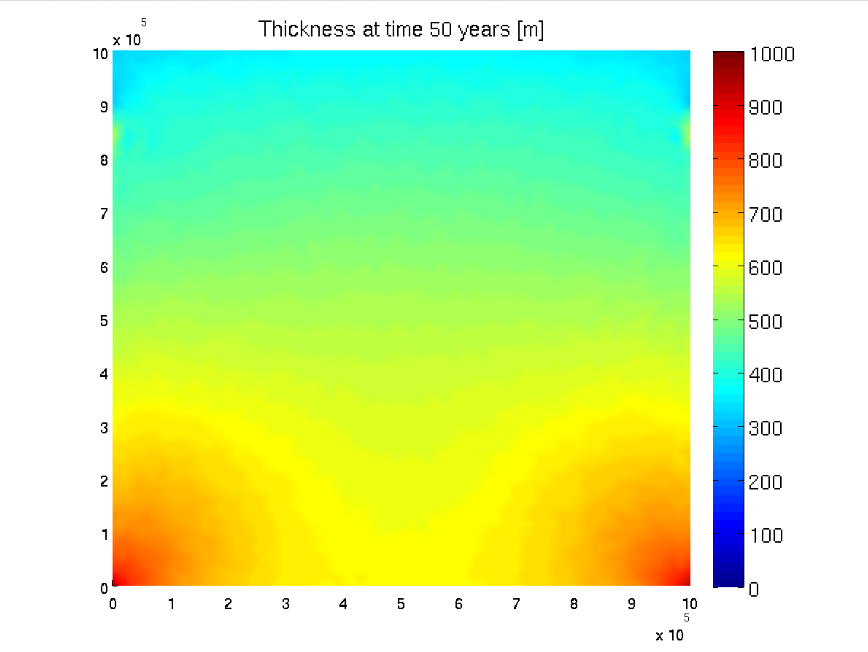


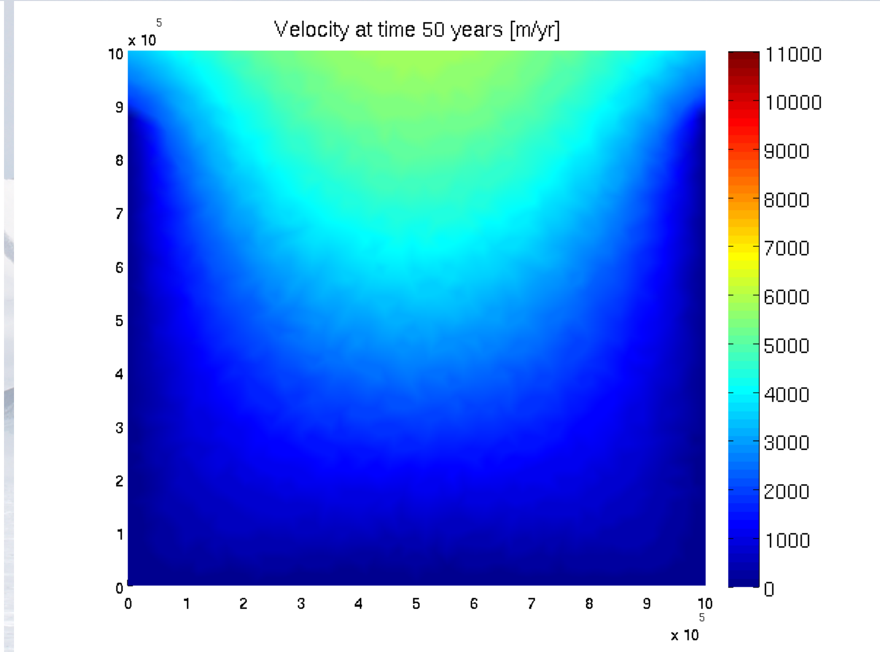


2. ISSM capabilities

Transient

- Simple transient run on a square ice shelf



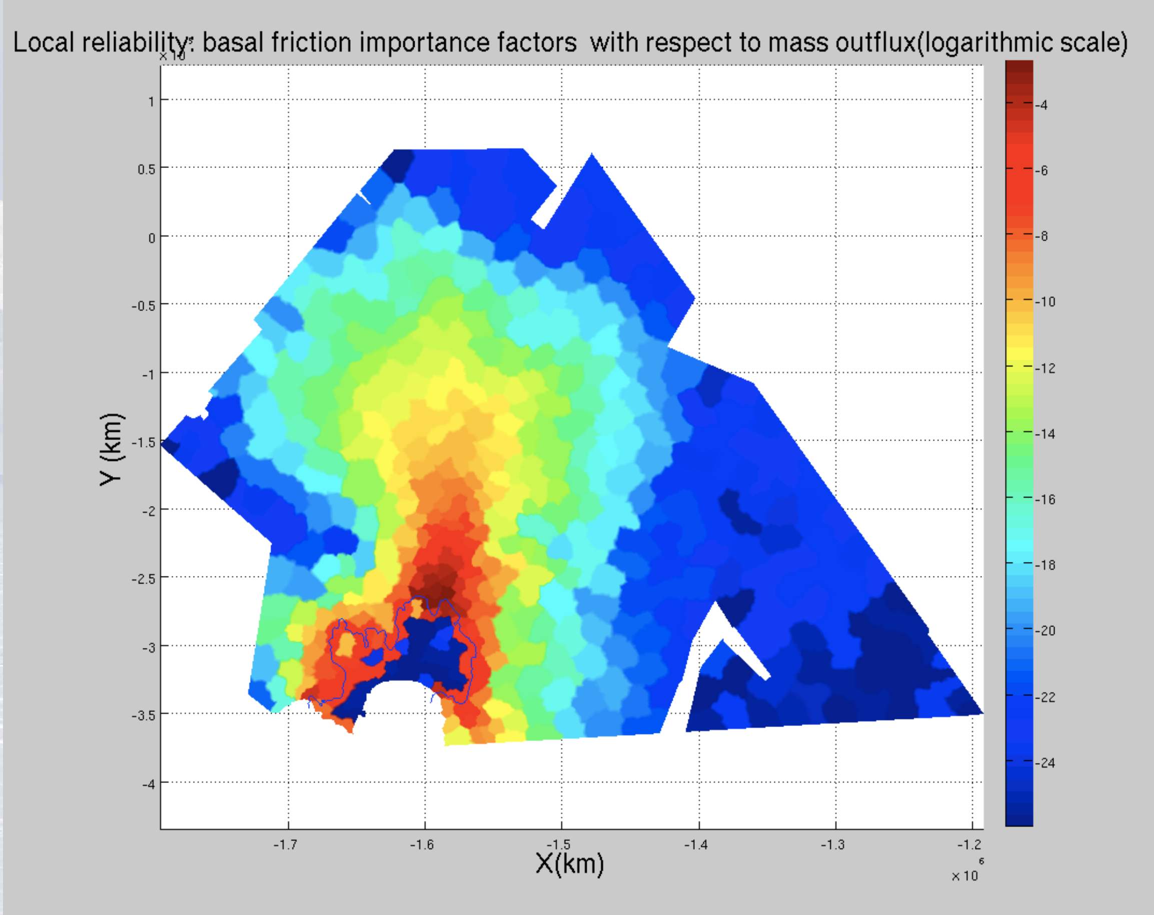


3. ISSM capabilities

Sensitivity analysis

- Dakota in embedded mode (Sandia National Lab)
  - Local reliability methods
  - Monte-Carlo (Latin Hypercube)
  - Parameter studies
  - Optimization

- For a given mass outflux error bar, it gives the spatial distribution of the precision we need for any dataset.



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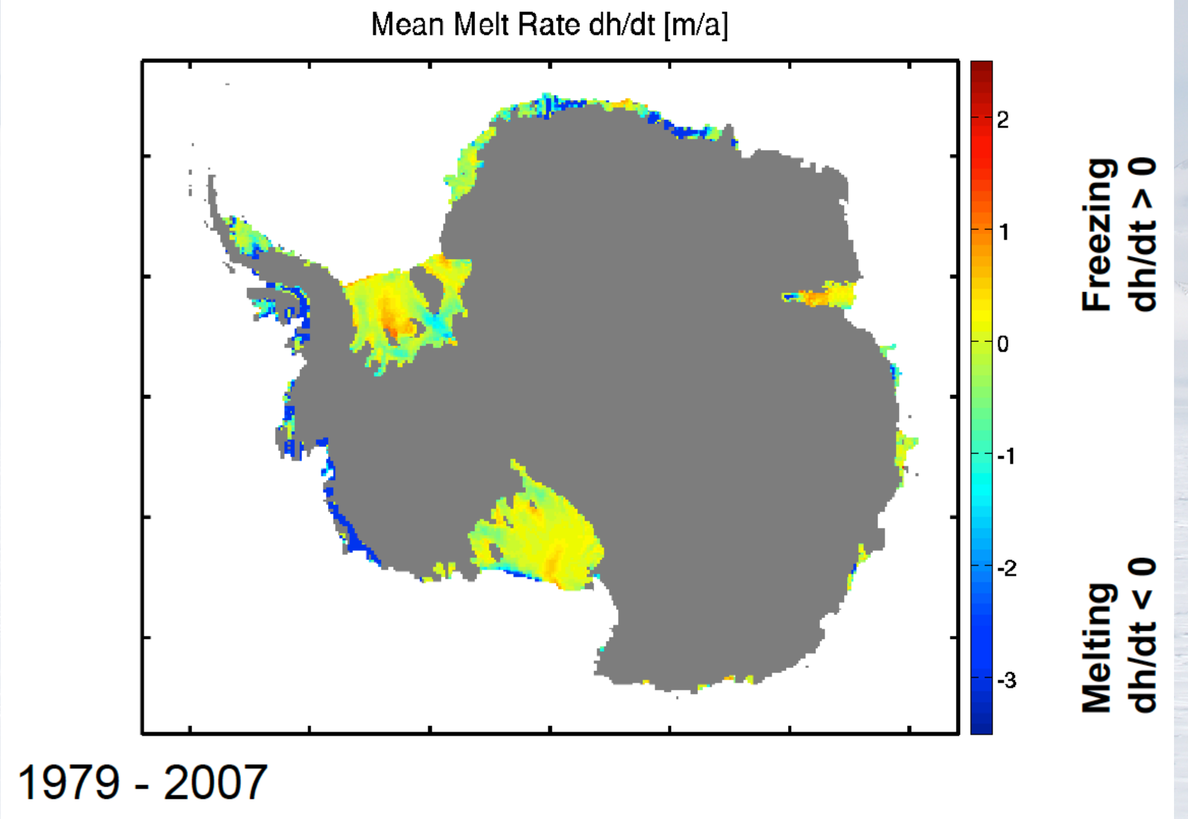
4. Perspectives

Future capabilities and challenges

Future capabilities:

- Moving boundary conditions
- Grounding line dynamics implemented at the 100 m spatial scale
- Calving law
- Hydrological model
- Ice-ocean interactions

- Coupling with ECCO2 framework (using MIT GCM)
  - melting under ice shelf cavities implemented by M. Schodlok, 2005
  - other processes: sub-glacial discharge, submarine melting of calving faces (Rignot et al., 2009)



Thanks !

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